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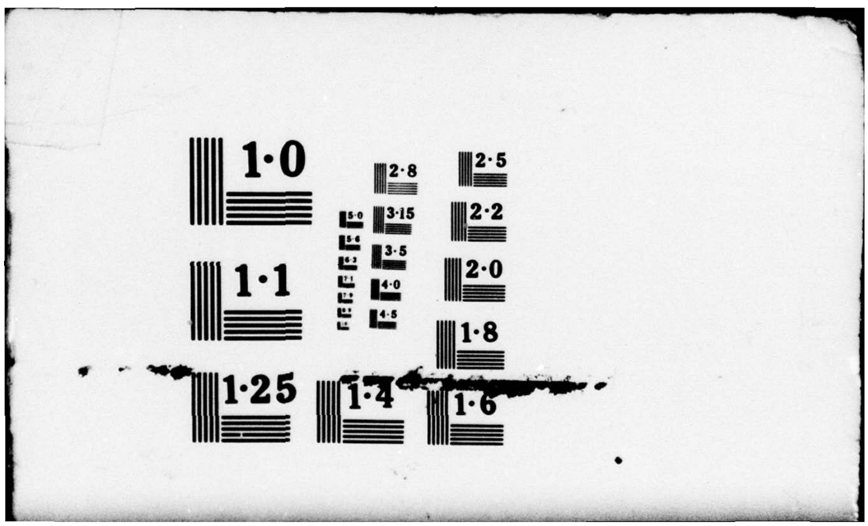
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Final Report CR-231

An Obscuring Aerosol Dispersion Model

VOLUME II
MODEL STRUCTURE

By

Ralph Zirkind

Prepared for:

U.S. Army ERADCOM
Night Vision and EO Laboratory
Fort Belvoir, Virginia
Contract No. DAAK02-74-C-0366

OPERATIONS ANALYSIS GROUP
GENERAL RESEARCH CORPORATION
A SUBSIDIARY OF FLOW GENERAL INC.
7655 Old Springhouse Road, McLean, Virginia 22102

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the development and exposition of a non-Gaussian aerosol dispersion model and the effect of the aerosol cloud on electrooptical systems. Explicitly, algorithms are provided to calculate both the transmitted and backscattered (glare) radiation components.

Finally, a validation of the model was performed with good to excellent agreement. This validation included the space-time history of cloud geometry and aerosol concentration.

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CONTENTS

1. INTRODUCTION

In Volume I we have presented the technical background and exposition of a model which describes the generation and dispersal of aerosols resulting from explosive and other smoke munitions. Here we have extracted the essential formalism and organized it into a step-by-step procedure which will permit the computation of (1) the spatial history of the aerosol cloud, (2) aerosol concentration, and (3) smoke (obscuring aerosol) transmittance. In view of the exothermic properties of white/red phosphorus (WP/RP) the clouds produced by WP/RP are treated separately; that is the effect of buoyancy is included.

We have listed here some pertinent data. Whenever extensive data are required the reader is referred to Volume I, e.g., list of munition characteristics.

With respect to the optical properties of smoke materials these are still in a state of flux and, therefore should be treated accordingly.

The adaption of this model to combat simulation models is not treated here; however, the necessary input data are listed. Further, we hav not altered the original (July 1977) suggestion that the smoke cloud may be treated as a transient loss of intervisibility, see the discussion in Volume I.

In Section 2 we consider the methods to compute the concentration of a smoke cloud and in Section 3 the transmission and other optical effects for both passive and active systems are considered.

In Appendix A, we give a discussion of the asymptotic values for plume heights.

2. COMPUTATION SCHEME FOR CLOUD CONCENTRATION

In this section a procedure is outlined to permit the determination of the concentration, C (gm/m^3), path length in the cloud, L (m), and, the important parameter, C•L (gm/m^2). The units used here are defined; however, we utilize primarily grams, meters and seconds. We initiate the discussion with the requisite input data and then proceed to the procedure proper.

2.1 Input Data

A. <u>Scenario</u>

Local target and observer locations
Munition deployment plan
Munition rate
Sensor type and operational wavelength band

B. <u>Smoke Munitions</u>

Type (Mk No, Caliber, etc.)
Fill weight (gm)
Fill material (WP, RP, HC, Oil, etc.)
Burn time and rate

C. <u>Meteorological Conditions</u>

$\left.\begin{array}{l}\text{Time of day}\\ \text{Cloud cover}\end{array}\right\}$ To establish stability category
Mean wind speed (m/sec) - surface to 10 m.
Temperature, T(°C) - @ 10 m and 0.5 m above ground level
Wind direction
Relative humidity (RH %)

D. <u>Optical Properties</u>

Scattering, absorption and extinction coefficients
Visibility, if eq. (28) and Tables 9 and 10 are used.

2.2 Determine Concentration for Single or Separate Multi-Munitions

2.2.1 Establish Stability Category

(a) Find $\Delta T = T(10\text{ m}) - T(.5\text{ m})$

if $\Delta T = 0.098°C$ then CAT D.

$\Delta T \lessgtr 0.098°C$ enter Table 1 with input data and find stability category

Table 1

PASQUILL STABILITY CATEGORIES

Surface wind speed at 10m (m/sec)	Day Insolation Strong	Moderate	Slight	Night thinly overcast or $\geq$ 4/8 low cloud	$\leq$ 3/8 cloud
< 2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

NOTE: If potential temperature, $\theta(T) = \Delta T + \Gamma$, is zero we have a neutral (D) category, i.e.,

$$\theta(T) = 0 = -0.098 + 0.098$$

2.2.2 Establish Cloud Dimensions

(a) Non-Exothermic (HC, oil, etc.)

$x = \bar{u} \cdot t$, $\bar{u}$ given in input data

$\left.\begin{matrix}\bar{y}\\ \bar{z}\end{matrix}\right\}$ with stability category enter Table 2 and find appropriate expressions. For more precise value of plume heights see Appendix G, Vol I.

where x = coordinate parallel to $\bar{u}$ (m)

$\bar{u}$ = time mean windspeed (m/sec)

t = time (sec)

Table 2

PLUME DIMENSIONS

Category	Width, $\bar{y}$ (m)	Height, $\bar{z}$ (m)	Remarks
A	9.1 + .419x	2.73 + .137x	Sunny day
B	9.1 + .328x	2.73 + .11x	Day, broken clouds
C	9.1 + .237x	2.73 + .073x	Overcast day/night
D	9.1 + .2x	2.73 + .06x	Neutral
E	9.1 + .18x	2.73 + .055x	Evening/early morning
F	9.1 + .146x	2.73 + .046x	Evening/early morning

For CAT D (see Appendix A)

$$z_{max} = \frac{150}{\bar{u}}, \quad \bar{u} > 0$$

For CAT E, F (see Appendix A)

$$z_{max} = \frac{75}{\bar{u}}, \quad \bar{u} > 0$$

(b) Exothermic (WP/RP)

Compute x, $\bar{y}$, $\bar{z}$ as above

To calculate the effect of heat on plume rise, Δh, i.e., to find

$Z = \bar{z} + \Delta h$, we follow the following procedures:

<u>Categories A, B & C:</u>

$$\Delta h = 1.6 \frac{F^{1/3}}{\bar{u}} x^{2/3}$$

$$F = 3.7 \times 10^{-5} H$$

H = 800x gms of WP/RP fill wt (gms) ÷ burn time in secs*

Z_{max} occurs when $C \equiv Q$(gms of smoke)/V(cloud volume in m³) $= 0.1\ g/m^3$

NOTE: Z_{max} will occur for times less than 40 secs. Method to calculate V is given later

* Burn time for explosive devices is 1 sec. Other munitions must be obtained from PM-Smoke or CSL.

Neutral Category D:

$$\Delta h = \frac{1.6F^{\frac{1}{2}}\, x^{*2/3}}{\bar{u}} \left[.4 + .64\left(\frac{x}{x^*}\right) + 2.2\left(\frac{x}{x^*}\right)^2\right]\left[1 + .8\,\frac{x}{x^*}\right]^{-2}$$

$$x^* = 0.52F^{.4}h_s^{.6}; \quad (h_s = 1 \text{ meter})$$

$(\Delta h)_{max}$ occurs for $3x^* \leq x \leq 5x^*$

Stable Categories E, F & G:

use Δh for unstable category except limit to a maximum value

$$(\Delta h)_{max} = 2.9\ (F/\bar{u}\bar{s})^{1/3}$$

$$x_{max} = 2.4\ \bar{u}/\bar{s}^{\frac{1}{2}} \text{ (see Appendix A)}$$

where $\bar{s} = \frac{g}{\bar{T}}\ \frac{\partial\Theta}{\partial z}$

$g = 9.8$ m/sec^2

$\bar{T}$ = mean ambient temperature (°K)

Θ = potential temperature

2.2.3 Establish Mass of Smoke Produced

(a) Specify smoke type and relative humidity

enter appropriate equation below and find yield

$Y(WP) = .003\ (RH - 40)^{1.67} + 2.9$

$Y(ZnCl_2) = .051\ (RH - 50)^{.85} + 1$

$Y(AlCl_3/H_2SO_4) = .016\ (RH - 20)^{1.24} + 1.4$

$Y(\text{Fog Oil}) = 1$

(b) Mass of smoke = Yield x Munition Fill Wt (gm)

2.2.4 Smoke Concentration

(a) Concentration for HC, Fog Oil, Metal Chlorides, etc.

$$C(t) = \frac{\text{Mass of smoke}}{\frac{\pi}{24} \cdot \bar{y}(t)^2 \cdot x(t)} \quad (g/m^3)$$

denominator = volume of semi-cone

(b) Concentration for WP/RP

$$C(t) = \frac{\text{Mass of smoke}}{\frac{\pi}{6}\ x(t)\ \bar{y}(t)\ Z(t)} \quad (g/m^3)$$

denominator = volume of ellipsoid/4.

NOTE: Establish value of $C(t) = 0.1$ gm/m³, thereafter $Z(t)$ remains constant. Reiterate on $C(t)$. Note: x and $\bar{y}$ continue to increase.

2.3 Smoke Path Length, L

(a) For a single munition; draw line-of-sight and find length through smoke cloud.

(b) For a multi-munition (mortars, artillery shells, bombs, smoke pots). Same as (a).

2.4 Calculate C•L

(a) For single munition, use appropriate result from (2.2) and (2.3).

(b) For multi-munition, use appropriate result (for single event) from (2.2) and (2.3) and then sum the result from n-rounds $\sum_{x=1}^{n} C_x \cdot L_x$

NOTE: For oblique viewing, the line-of-sight may initially intercept only a portion of the expanding smoke cloud.

3. CONCENTRATION FOR CONTINUOUS LINEAR SMOKE SOURCE OF LENGTH, ℓ

(a) Stability category - Find y(t); z or Z.

(b) Calculate concentration

$$C(t) = \frac{\text{Mass of Smoke}}{\ell \cdot t \cdot \bar{u}} \; \frac{1}{\frac{\pi}{12} \cdot Z(t) \cdot (1+k)} \quad (g/m^3)$$

Mass of Smoke = Total weight x yield (gms); 2.2.3.

ℓ = length of smoke (m)

t = burn time of smoke material (sec)

$\bar{u}$ = mean wind speed (m/sec)

Z(t) = cloud height (m)

k = cloud width increment; $y(t)/\ell$

(c) Smoke Path Length, L

Draw line-of-sight through smoke cloud.

(d) Concentration x Path Length

(2) x (3) = C•L

3.1 Two dimensional or Several Linear Smoke Sources

See Volume I, pps 73-76 and Appendix D.

4. TRANSMISSION AND OPTICAL EFFECTS

We consider here only the transmission through smoke and other optical effects, e.g., glare, produced by a smoke cloud. The remainder of the path between target and observer is not treated here since computer programs exist to perform this calculation. We will first

consider passive systems and, then attempt to outline a procedure for active (laser) systems.

4.1 Transmission, T: Passive Systems

(a) Determine sensor wavelength or passband-lookup extinction, scattering and absorption coefficients for smoke type.

(b) Establish sensor field-of-view and target radiation angle.

NOTES: (1) For viewing systems, e.g., FLIR, use instantaneous field-of-view and not total field-of-view.

(2) Passive targets are normally LAMBERTIAN. Searchlights etc. are collimated sources.

4.1.1 LAMBERTIAN Radiator

Transmission = $(1+\alpha_s \cdot L \cdot D)\ \exp-[\alpha_e(m) \cdot C \cdot L]$

The value for D is given below for several wavelengths and three receiver fields-of-view, ϕ, = .5, 5 & 10.

	D		
$\lambda(\mu m)$	.5°	5°	10°
0.5	-	.40	.60
1.0	-	.30	.50
5.0	-	.10	.20
10.0	-	.05	.10

NOTE: D = correction for scattering

α_s = scattering coefficient (m^{-1})

$\alpha_e(m)$ = extinction coefficient (m^2/gm)

The correction for scattering is only important for visible and near infrared systems.

Whenever the coefficients vary within a passband, then integration over the band should be performed.

4.1.2 Collimated Sources

A simpler form for transmittance may be used for collimated sources

$$T = [1 + \alpha_s \cdot L \cdot \phi] \cdot \exp[-\alpha_e \cdot L]$$

where ϕ = receiver f.o.v. in degrees/180.

NOTE: A laser transmitter is a collimated source and the spectral extinction coefficient $\alpha_e(\lambda) = \alpha_e(\lambda, m) \cdot C$ in units of m^{-1}

NOTICE: Establish system criterion for transmission as to lower permissible limit, i.e., if $T \leq$ limit then terminate calculation.

5. CONTRAST, C

5.1 Visual and Near Infrared: Daytime

We use the Blackwell definition of contrast, namely

$$\frac{|\text{Target Brightness} - \text{Background Brightness}|}{\text{Background Brightness}}$$

C_o is the contrast at the scene. The contrast C_R, at observer is defined by the expression

$$C_R = C_o \left[1 + \frac{S_K}{G} \left(e^{\alpha_e R} - 1\right)\right]^{-1}$$

R = distance of cloud edge to observer (m)

Apply test if $C_R < 5\%$

(a) For sunny day $S_K/G = .2/\beta$

(b) Other conditions $S_K/G = 1/\beta$

Value of β is given in Table 3 for different values of α_s/α_e, $\alpha_e \cdot L$.

Table 3

VALUES OF β

α_s/α_e	$\alpha_e \cdot L$: 0	0.5	1.0	2	3
.1	0	.00	.0	.015	.02
.3	-	.02	.03	.045	.05
.5	-	.04	.07	.09	.10
.7	-	.08	.12	.17	.19
.9	-	.14	.25	.33	.37
.95	-	.22	.35	.43	.47
1.0	-	.22	.35	.50	.59

The values for α_s/α_e for HC and WP smoke clouds are tabulated below:

Table 4

WAVELENGTH DEPENDENCE OF α_s/α_e

$\lambda(\mu m)$	α_s/α_e: HC	WP
≤ 1	1	1
2.0	1	-
2.5	.974	-
3.0	.474	.249
3.5	.841	.242
4.0	.894	.274
4.5	.876	.255
5.0	.835	.256
8.0	.485	.042
8.5	.392	.043
9.0	.309	.050
9.5	.245	.036
10.0	.184	.067

Table 4 (Cont'd)

$\lambda(\mu m)$	α_s/α_e HC	WP
10.5	.129	.126
11.0	.088	.123
11.5	.055	.133
12.0	.033	.102
12.5	.029	-
13.0	.023	-

NOTE: If $\alpha_e \cdot L > 3$, transmission $\leq$ 5% and therefore no need to calculate contrast reduction.

If C_R > 5% then utilize simple result or, the one described in Volume 1, pps 53-55.

5.2 Near Infrared: Nighttime

Use simple procedure with night sky spectral irradiance curve in place of solar irradiance.

5.3 Mid-IR (3-5μm)

We describe here only the glare contribution due to solar scattering from the smoke cloud as the contrast loss due to the ambient environment is treated elsewhere. We recommend here the use of the expression

$$N_\lambda(e) = H(S) \cdot \tau_i(\lambda) \cdot \frac{\alpha_s(\lambda)}{\alpha_e(\lambda)} \cdot \frac{P(\Theta)}{4\pi} \cdot \frac{\cos i}{\cos i + \cos e}$$

$H(S)$ = solar irradiance

$P(\Theta)$ = differential scattering/unit cloud area/steradian

$\cos i, e$ = cosine of angle of incidence and exitance

$\tau_i(\lambda)$ = atmospheric spectral transmittance from source to cloud

$N_\lambda(e)$ = spectral steradiance exiting from cloud

NOTES: 1. For passband, integration of all parameters on right hand side is necessary.

2. Values of $P(\Theta)$, etc, must be obtained from Mie program or experiment.

5.4 LWIR (8-13μm); (3-5μm, Nighttime)

Cloud glare is not important, no calculation is required.

6. LASER SYSTEMS

6.1 Transmission

See 4.1 for one way pass; i.e., cloud between transmitter and receiver.

When cloud exists between receiver and laser illuminated target use Section 4.1.1. Add solar background (cloud backscatter) clutter where the receiver pass-band ($\Delta\lambda$) must be used.

6.2 Backscatter

See Section 5.3 for appropriate expression. The value for $P(\Theta)$ must be measured or computed from Mie scattering theory. The latter is available from C.S.L. Aberdeen (J. Vervier).

7. THERMAL EFFECTS

In the above described model we have assumed the cloud concentration to be homogeneous. Estimates of the material and vertical distributions are discussed in Volume I; however, these distributions may not present sufficiently severe gradients to affect thermal viewing or laser systems. A detailed analysis of the cloud structure will be performed in an upgraded model.

A problem to thermal or laser systems that can be readily identified is the multiple source; that is, if a number of phosphorus sources exist false targets will be generated in the field of view. This effect is identical to scene clutter and should be treated accordingly.

Appendix A

Plume Rise Limiting Values

The purpose of this appendix is to clarify the several rules governing the maximum values that the exothermic smoke plume can achieve and explain the additional rules added here in Section 2.2.2 for non-exothermic smokes/aerosols. We will first consider the non-exothermic obscurant.

In Table 2, Section 2.2.2, we define the plume rise as a monotonic increasing linear function of x, i.e., $\bar{z} = A + Bx$. For atmospheric conditions defined as Pasquill Category D (neutral) and Categories E & F (stable) we have established, on the basis of data analysis, that the cloud stabilizes at specific heights; that is, the maximum height can be defined at each value of x, the horizontal displacement, by $A/\bar{u}$ where A is a constant. A set of values is given in Table A.1 below.

TABLE A.1

MAXIMUM VALUES FOR PLUME RISE

	$\bar{u} \cdot z_{max}$ (m^2/s) Stability Category	
x(m)	Neutral	E&F
250	60	25
500	105	55
1000	150	75

Let us now consider the case of a neutral category with $\bar{u} = 5$ m/s. Then, from Table A.1 the z_{max} at x = 250m is 12m whereas from Table 2, $z = 2.73 + .06x = 2.73 + 15 = 17.7$. If we attribute the value of 2.73 to source dispersion at x=0 then the difference is ~25%. One finds by the same procedure that the difference at 100 m is ~15%. On the other hand if we let x = 1000 m we have from Table A.1 that z_{max} = 30 m and from Table 2, z = 60 m or, 100% difference. We assert that the plume rise equations in Table 2 represent the linear portion of the rise and as the plume becomes bent due to the horizontal wind (mean value $\bar{u}$) other expressions, as given in Table A.1, are applicable. Hence it is recommended that Table A.1 be used for $x \geq 250$ m.

For <u>exothermic smokes</u>, we stated that the maximum rise due to buoyancy under stable atmospheric conditions is

$$\Delta h = 2.9\ (F/\bar{u}\bar{s})^{1/3}, \tag{1}$$

where F is the rate of heat released, and should occur at a maximum value of $x = 2.4\ \bar{u}/\bar{s}^{1/2}$. The general rise has been defined by

$$h = 1.6\ \frac{F^{1/3}}{\bar{u}}\ x^{2/3}(F^{1/6}) \tag{2}$$

where we added the extra multiplier $F^{1/6}$, i.e., we altered the exponent of F from $1/3$ to $1/2$, to agree with experimental results for WP munitions. If we take the conventional value $(F^{1/3})$ in eq. (2) and equate eq. (1), we find that the maximum rise will occr at

$$x_{max} = 2.4\bar{u}/\bar{s}^{1/2} \tag{3}$$

which is independent of "F". On the other hand, the explicit use of eq. (2) gives for x_{max}

$$x_{max} = 2.4\bar{u}/\bar{s}^{1/2} \cdot F^{1/4} \tag{4}$$

The appearance of "F" in eq. (3) raises some questions. First, as $F \to 0$, $x_{max} \to \infty$ (and $\Delta h \to 0$) a condition which probably is not physically meaningful. Secondly, when $F \to \infty$, $x_{max} \to 0$ we have a condition that is questionable; that is, the buoyancy will dissipate at $x \sim 0$. The reader is reminded that the <u>established criterion, namely the plume rise due to buoyancy be terminated when the smoke concentration drops to 0.1 g/m³</u>; is also applicable.

In the next edition of this model, the questions raised here relative to complete internal self-consistency will be addressed and resolved.

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